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# RESIDUAL STRESS EFFECTS UPON SIF DISTRIBUTION FOR CRACKS PARALLEL TO AND WITHIN BOND LINES IN RUBBERLIKE MATERIALS

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## ABSTRACT

As a result of the need to extend the storage life of rocket motors, new emphasis has been placed upon the effect of cracks developed during storage and transport on the integrity of motor performance. In addressing this need, the authors have developed a three specimen test procedure for evaluating the stress intensity factor (SIF) distribution for cracks through the thickness of rubberlike materials near to and within simulated bond lines between the motor grain and its liner. A refined frozen stress method is employed for making measurements, and preliminary studies have shown that, for cracks in the bond line under both Mode I and Mixed Mode loads, the stress intensity factors are elevated primarily due to bond line residual stresses and may not be affected by modulus mismatch.

In the present study, the refined frozen stress method is applied with the three specimen technique to edge cracks which are both parallel to and within the bond line. Since the three specimen method utilizes both homogeneous bonded and bimaterial bonded specimens, the bond line effect is separated from modulus mismatch effects. Results of the study show that cracks parallel to the bond line develop both an elevated Mode I SIF and a shear mode as they are placed closer to the bond line. These effects are shown to be due to critical temperature ( $T_c$ ) mismatch. Cracks in the bond line exhibit a somewhat elevated SIF but no shear mode. The SIF elevation is mainly due to residual bond line stress and modulus mismatch is shown to have virtually no effect.

## INTRODUCTION

Beginning in 1993, the authors undertook an experimental program directed towards an evaluation of the frozen stress photoelastic method for determining the stress intensity factor (SIF) distribution along cracks located near to or within bond lines joining different incompressible materials with substantial thickness. The objective was to approximately simulate such distributions for cracks within or near to the bond line between rocket motors and their liners. It was expected that there would be residual stress resulting from the bonding procedure. Moreover, it had been shown analytically [1] that when plane strain exists where incompressible materials have been joined, then the interface fracture equations reduce to the classical homogeneous form, thus allowing separation of the Mode I and Mode II stress intensity factors. It was felt that such would be approximately the case for rocket motor material in a state of generalized plane strain.

## EXPERIMENTAL PROCEDURES

In order to separate residual stress effects from modulus mismatch, a three specimen test procedure was employed: i) An edge cracked homogeneous control specimen, ii) A bonded homogeneous specimen containing an edge crack and iii) A bimaterial edge cracked specimen. Two types of bimaterial specimens were employed. Their material properties are given in Table I. Specimens A included homogeneous Araldite specimens and homogeneous bonded Araldite and Specimens B included homogeneous PLM4B specimens and homogeneous bonded PLM4B specimens. Ideally, the two materials employed in the bimaterial specimens should have identical properties except for modulus in order to assess modulus mismatch effects. As indicated in Table I, it was not possible to fully match all material properties except modulus. In bimaterial specimens A,

the thermal coefficients differed by 17% at critical temperature, and in bimaterial specimens B, the critical temperatures differed by about 13%.

Since it was crucial that accurate dimensions be achieved along the crack front it was decided to machine in the cracks with a round tipped Buehler saw. The bond line thickness was kept small but finite and constant. All of the near tip test data were collected outside the bond line because the bond line material, being different from the adherends, produced a local disturbance which we considered part of the near tip nonlinear zone. Test specimen dimensions are shown in Fig. 1.

All test specimens were first subjected to a no load stress freezing cycle after which stress freezing under load was carried out. Both through the thickness (tt) and thin slices (L,M,R) (Fig. 1) were analyzed photoelastically, the latter being accomplished by employing the Post and Tardy Methods in tandem for increasing fringe sensitivity and using the algorithms in the Appendix for converting optical data into SIF values. All photos used bright fields.

Reasonable success [2]-[4] had been achieved in measuring SIF distributions by employing the A material combination for cracks within the bond line for both Mode I and Mixed Mode conditions. The present study was focused primarily on evaluating the effect of critical temperature ( $T_c$ ) and modulus mismatch in the B material combination for cracks parallel to and within the bond line.

### RESULTS AND DISCUSSION

By placing the cracks in the higher  $T_c$  material (PSM9) in the B specimens, it was felt that the  $T_c$  effect would be minimized. The idea was that, since the lower  $T_c$  material (PLM4B) would still be rubbery when the PSM9 turned glassy, then the modulus ratio of  $E_{PLM4B}^{Rubbery} / E_{PSM9}^{Glassy} \approx 0.5\%$  should negligibly affect the SIF values in the PSM9. Then, when the PLM4B became glassy, it would only slightly stress the PSM9 and this live stress would be removed upon slicing. While the no load tests revealed a near tip residual stress field, (Fig. 2a) the fringe order varied little over the data range, indicating that the residual stresses affected mainly the non-singular part of the data and only slightly the stress gradient. Thus it had small effect upon the SIF values. None of the homogeneous bonded specimens using the B material combination revealed any increase in the average SIF above the homogeneous specimen value and no shear mode was observed. However for the bimaterial specimens, a small shear mode, for which the reading angle ( $\theta_R$ ) increased as the crack was moved closer to the bond line, was observed. Moreover, for the crack nearest the bond line, (Fig. 2b,c) the value of  $K_I$  increased by 29%, but no increase was observed for cracks further from the bond line (i.e.,  $h = 0.25$  in. (6.35mm), 0.50 in. (12.7mm)).

In order to clarify whether or not this increase was due to modulus mismatch or  $T_c$  mismatch, another test was run with the A material combination which duplicated the above noted geometry (i.e.,  $h = 0.125$  in (3.18mm), Fig. 1) The loaded (tt) fringe pattern is shown in Fig. 3. Data for analysis were taken only above the crack within the indicated data zone. The fringe pattern reveals no fringe loop rotation, and hence no Mode II and the value of  $K_I$  was the same as from a 2D analysis, indicating no increase due to the bond line proximity. These results confirm that both the shear mode and the increase in the SIF found in the test shown in Fig. 2 were due to  $T_c$  mismatch and not to modulus mismatch.

A final test was conducted on the B material with the crack within the bond line. Fringe patterns from the bimaterial tests are shown in Fig. 4, indicating the data zone. In interpreting these patterns, it should be noted that even for pure Mode I (which is observed here) the fringes will not be symmetric with respect to the crack or the bond line due to the difference in the material fringe values (Table I) for the two materials. The absence of the shear mode for this case was also predicted in Ref. [1]. Analysis of the fringe data showed no significant difference between the bimaterial and homogeneous bonded test data, again indicating no bimaterial effect on the SIF values.

Fig. 5 which is a closeup of the (tt) loaded Fig. 4 photo reveals several features. In this test, the bond line adhesive was the same material as the upper material PSM9 and so has the same  $T_c$ . Nevertheless, at the upper edge of the bond line, some distortion of the fringes still occurs near the crack tip indicating the presence of fringe order mismatch between PSM9 and the glue but not as severe as along the bottom of the bond line where the PSM9 meets the PLM4B.

Typical SIF distributions from the A material combination are compared to their homogeneous bonded counterparts in Fig. 6. These results clearly show that bimaterial effects are not significant and that reasonable SIF distributions can be measured by the method employed. It is interesting to note that when the crack is placed in the bond line for the B material combination, the shear mode vanishes which suggests

that if one is only interested in problems for cracks within the bond line, then the  $T_c$  mismatch does not appear to have a significant effect for incompressible materials under generalized plane strain.

#### SUMMARY

Using a three specimen test procedure, a convenient incompressible bi-material combination (B) was evaluated for predicting SIF levels and distributions in cracks parallel to and within bimaterial specimens. By comparing results with those from a previously used material combination (A) it was shown that  $T_c$  mismatch in the B combination induced both a shear mode and an elevation in SIF level for cracks very near the bond line. However, for cracks away from the bond line or within the bond line, the B material combination yielded reasonable Mode I results.

It is important to note that the fact that modulus mismatch, shown earlier to have no effect on cracks within the bond line of A materials was also confirmed here for cracks parallel to the bond line as well as within the bond line.

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Table I

Material A	$T_{critical}$	$E_{Hot}$	$f_r$
Araldite	240°F	2698 psi (18.60 MPa)	1.64 psi-in (286.9 Pa-m)
Aral-Alum	240°F	5349 psi (36.88 MPa)	—

Matched thermal coefficients at 68° F.;  $\alpha = 15.3 \times 10^{-6}$  per °F. At critical temperature ( $T_c$ ) thermal coefficients were  $119 \times 10^{-6} 20 \pm 10^{-6}$  per °F.

Material B	$T_{critical}$	$E_{Hot}$	$f_r$
PSM4B	180°F	1879 psi (12.96 MPa)	2.40 psi-in (420.3 Pa-m)
PSM9	205°F	6912 psi (47.67 MPa)	2.97 psi-in (520.1 Pa-m)

These materials have the same thermal coefficients at room temperature ( $T_R$ ) and critical temperature ( $T_C$ ). They were  $\alpha_{RT} = 39 \times 10^{-6}/°F$  and  $\alpha_{CT} = 90 \times 10^{-6}/°F$  respectively. Bonding agent was liquid PSM9.

#### APPENDIX

##### MODE I ALGORITHM

Beginning with the Griffith-Irwin Equations, we may write, for Mode I, for the homogeneous case,

$$\sigma_{ij} = \frac{K_1}{(2\pi r)^{\frac{1}{2}}} f_{ij}(\theta) + \sigma_{ij}^0 \quad (i,j = x, z) \quad (1)$$

where:

$\sigma_{ij}$  are components of stress  
 $K_1$  is SIF